CIT - ELECTRON TUBE & MICROWAVE
LABORATORY REPORT

# FINAL REVIEW REPORT

to

U.S. Office of Naval Research

from

California Institute of Technology

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA

FINAL REVIEW REPORT

to

U.S. Office of Naval Research

from

California Institute of Technology

Submitted by

R. W. Gould

A. Yariv

R. S. Harp

Contract Nonr 220(50)

September 1, 1963 to September 1, 1969

August 31, 1970

## I. INTRODUCTION

This report covers briefly the research performed under Contract Nonr 220(50) between September 1, 1963 and September 1, 1969. This contract was a continuation of a previous contract, Nonr 220(13), and in some cases carried through without interruption projects begun under the former contract. Equipment used under the former contract was continued under Nonr 220(50).

The research was both theoretical and experimental and generally covered the following areas:

Plasma wave resonances in spatially non-uniform plasmas
Cyclotron and upper hybrid echo phenomena in plasmas
Plasma wave echoes
Cyclotron harmonic waves in plasmas
Resonance cones in anisotropic plasmas
Recombination radiation from forward biased p-n junctions
Electro-optic effect
Infrared absorption in gallium arsenide
Modes in optical resonators with gain

The results of the research were circulated in the form of O.N.R. Technical Reports and published articles in technical journals, lists of which appear in Sections III and IV of this report.

## II. PERSONNEL

During the entire duration of this contract the principal investigator was Professor Roy W. Gould. Professors Amnon Yariv and R. S. Harp also took part in this program, assisted at different times by various Research Fellows and Graduate Students. Seven graduate students received their Ph.D. degrees with the support of this contract.

Biographical data follows.

ROY W. GOULD - BIOGRAPHY

Roy W. Gould received his bachelor's degree with honors from the California Institute of Technology in 1949 and his master's degree in electrical engineering from Stanford University in 1950. He received the PhD degree summa cum laude in physics in 1956 from Caltech. His doctoral thesis research was in two parts (a) Plasma Oscillations and Radio Noise from the Disturbed Sun, and (b) A Field Analysis of the M-Type Backward Wave Oscillator.

Between 1950 and 1952 Mr. Gould was engaged in reactor design with North American Aviation and the development of a portion of the Corporal missile guidance system. Between 1953 and 1955 he was a Howard Hughes Fellow engaged in part-time research with the Hughes Electron Tube Laboratory. During this time he contributed substantially to the development of high power traveling wave tubes for military radar systems. He continued this work from 1955 until 1960 as a consultant.

Dr. Gould was an Assistant Professor of Electrical Engineering at Caltech from 1955 to 1958; an Associate Professor of E.E. from 1958 to 1960; an Associate Professor of Electrical Engineering and Physics from 1960 to 1962 and a Professor of Electrical Engineering and Physics from 1962 to the present. His research interests are in plasma physics and microwave electronics. Work in these fields by Professor Gould is supported jointly by the Office of Naval Research and the Atomic Energy Commission. This work has resulted in numerous technical reports, journal publications, and talks at research conferences.

Professor Gould has contributed to a report on basic research in electronics prepared for the Office of the Assistant Secretary for Defense (Research and Development) and a classified "state-of-the-art" report on microwave electron tubes for the same office (1958). He is a Fellow of the American Physical Society and has served on the executive committee of its division of plasma physics. In 1965 he was elected a Fellow of the Institute of Electrical and Electronic Engineers "for contributions to the theory of microwave tubes" and served on the editorial board of the IEEE Proceedings. He is a member of the International Scientific Radio Union (Commission VII) and is serving as an associate editor (for plasmas) of Radio Science, and as an associate editor of the Physics of Fluids.

Professor Gould has also served as a consultant to various industrial research laboratories, principally Hughes Research Laboratories and Microwave Associates (for microwave electronics); Aerospace, General Atomic Division of General Dynamics (for plasma physics and controlled fusion research), and the Oak Ridge National Laboratory (Director's Advisory Committee for CTR).

During the year 1963-64 Professor Gould was on a year's leave from Caltech on a National Science Foundation Postdoctoral Fellowship for research at the Max Planck Institute for Physics and Astrophysics, Munich, Germany; and the United Kingdom Atomic Energy Authority, Culham, England. During the summer of 1964 he was on leave to the Max Planck Institute for Extraterrestrial Physics, Garching at Munich.

Dr. Gould is currently on leave from Caltech with the U. S. Atomic Energy Commission as Assistant Director (for Controlled Thermonuclear Research), Division of Research.

AMNON YARIV - BIOGRAPHY

Amnon Yariv was born in Tel Aviv, Israel on April 13, 1930. A veteran of the Israeli war of independence, he came to the United States in 1951 and obtained the B.S. (1954), M.S. (1956) and Ph.D. (1958) in electrical engineering from the University of California in Berkeley.

He went to the Bell Telephone Laboratories, Murray Hill, New Jersey in 1959, joining the early stages of the laser effort. He came to the California Institute of Technology in 1964 as an Associate Professor of Electrical Engineering, becoming a Professor in 1966.

On the technical side, he took part (with various co-workers) in the discovery of a number of early solid state laser systems, in the formulation of the theory of parametric quantum noise and the prediction of parametric fluorescence, and in the invention of the technique of mode-locked ultrashort-pulse lasers and FM lasers.

His present research efforts are in the areas of nonlinear optics, infrared electro-optical materials, and recombination mechanisms in semiconductors.

He is an author of a text Quantum Electronics and an Associate Editor of the IEEE Journal of Quantum Electronics, as well as an industrial consultant to a number of aerospace firms and the Institute for Defense Analysis.

Dr. Yariv is a member of the American Physical Society, Phi Beta Kappa, and a Fellow of the Institute of Electrical and Electronics Engineers.

ROBERT S. HARP

CURRICULUM VITAE

Date of Birth: February 20, 1937

Place of Birth: Jersey City, New Jersey

Citizenship: USA

1954: Received first prize at the West Virginia State Science Fair for an exhibit of remote control. Presented with award from the Engineers Club of Huntington, West Virginia, as the Outstanding High School Graduate in Science and Engineering.

1954-1955: Studied at the University of Kentucky.

1955-1959: Studied at Massachusetts Institute of Technology, majoring in Physics. Received the B.S. degree in 1959. Summer jobs included work with heavy electrical machinery, design and testing of microwave antennas, and related microwave measurements.

1959-1960: Worked as a trouble shooter for microwave and communications gear in Alaska on the DEW line. Duties included emergency repair responsibilities for the POW Sector, and on-the-job training and testing of technicians.

1960-1964: Resumed studies at Stanford University in Electrical Engineering. Received M.S. degree in 1961. Grade Point average 3.85/4 preceding the Ph.D. Qualifying Examination. Graduate research was in the field of Plasma Physics under Prof. G. S. Kino. Dissertation Title: "A Study of the Plasma Boundary."

1964-1965: Continued research at the Institut für Plasmaphysik, Munich, Germany, as a National Science Foundation Postdoctoral Fellow.

1965-1967 Continuing work in Plasma Physics at Stanford University as a Research Associate.

1967-Present Assistant Professor of Electrical Engineering at California Institute of Technology.

## III

## Technical Articles published under

## Contract Nonr 220(50)

| Author | | |
|---|---|---|
| W. H. Kegel | "Pulse-Stimulated Radiation from a Plasma at Harmonics of the Gyrofrequency", Plasma Physics 9, 339 (1967). | 1967 |
| R. W. Gould<br>T. M. O'Neil<br>J. H. Malmberg | "Plasma Wave Echo", Physical Review Letters 19, 219 (1967). | 7/31/67 |
| R. W. Gould | "Echoes in Collision-Free Plasmas", Physics Letters 25A, 559 (1967). | 10/9/67 |
| T. M. O'Neil<br>R. W. Gould | "Temporal and Spatial Plasma Wave Echoes", The Physics of Fluids 11, 134 (1968). | Jan.1968 |
| L.O. Bauer<br>F. A. Blum<br>R. W. Gould | "Plasma Echoes at Upper Hybrid Resonance", Physical Review Letters 20, 435 (1968). | 2/26/68 |
| R. K. Fisher<br>R. W. Gould | "Resonance Cones in the Field Pattern of a Short Antenna in an Anisotropic Plasma", Physical Review Letters 22, 1093 (1969). | 5/26/69 |
| F. A. Blum<br>L. O. Bauer<br>R. W. Gould<br>R. L. Stenzel | "Microwave Scattering and Noise Emission from Afterglow Plasmas in a Magnetic Field", The Physics of Fluids 12, 1018 (1969). | May 1969 |
| R. K. Fisher<br>R. W. Gould | "Resonance Cone Structure in Warm Anisotropic Plasma", Physics Letters 31A, 235 (1970). | 3/9/70 |
| R. S. Harp<br>R. R. Smith | "Microwave Pulse Amplification by Plasmas", Physics Letters 29A, 317 (1969). | June 1969 |
| A. Yariv<br>C. A. Mead<br>J. V. Parker | "GaAs as an Electrooptic Modulator at 10.6 Microns", IEEE Jour. Quantum Electronics QE2, 243 (1966). | Aug. 1966 |
| A. Yariv | "Parametric Amplification and Frequency Conversion in Magneto-Plasmas", Proc. 7th Int. Conf. on Phenomena in Ionized Gases, Vol. II, p. 462, Belgrade 1966. | 1966 |
| T. C. McGill<br>A. Yariv | "Ionic Model for the Linear Electro-Optic Effect", Physics Letters 25A, 411 (1967). | 9/25/67 |

| Author | | |
|---|---|---|
| J. Comly<br>E. Garmire<br>A. Yariv | "Infrared Absorption at 10.6μ in GaAs" Jour. of Appl. Phys. 38, 4001 (1967). | Sept. 1967 |
| L. Casperson<br>A. Yariv | "The Gaussian Mode in Optical Resonators with a Radial Gain Profile", Applied Phys. Letters 12, 355 (1968). | 5/15/68 |

## IV

## TECHNICAL REPORTS

### Contract Nonr 220(50)

| Report # | | |
|---|---|---|
| 21 | Resonance Oscillations in a Hot Nonuniform Plasma Column, by J. C. Nickel, J. V. Parker, R. W. Gould | Sept. 1963 |
| 22 | Experimental Study of Plasma Wave Resonances in a Hot Nonuniform Plasma Column, by J. C. Nickel | May 1964 |
| 23 | Theory of Plasma Wave Resonances in a Hot Nonuniform Plasma, by J. V. Parker | June 1964 |
| 24 | Resonance Oscillations in a Hot Non-Uniform Plasma, by J. C. Nickel, J. V. Parker, R. W. Gould; also, published in The Physics of Fluids 7, 1489 (1964). | Sept. 1964 |
| 25 | Directed Electron Velocity Distributions in Rare Gas Discharges Using Guard Ring Probes, by R. H. Bond | June 1965 |
| 26 | A Model for Pulse Stimulated Emission from a Plasma by W. H. Kegel | Aug. 1965 |
| 27 | Theory of Pulse Stimulated Radiation from a Plasma Caused by the Relativistic Mass Effect, by W. H. Kegel | Dec. 1965 |
| 28 | Cyclotron Echo Phenomena, by R. W. Gould | Dec. 1965 |
| 29 | Echo Phenomena, by R. W. Gould | Dec. 1965 |
| 30 | On the Theory of Pulse Stimulated Radiation from a Plasma, by W. H. Kegel and R. W. Gould; also, published in Physics Letters 19, 531 (1965). | Nov. 1965 |
| 31 | Single Pulse Response of a Plasma, by R. W. Gould | May 1966 |
| 32 | Pulse Stimulated Radiation from a Plasma at Harmonics of the Gyrofrequency, by W. H. Kegel | June 1966 |
| 33 | A Nonlinear Study of Beam Plasma Amplification, by R. L. Poeschel | Sept. 1966 |
| 34 | Pulse Stimulated Radiation from a Plasma Involving the Second Harmonic of the Gyrofrequency, by W. H. Kegel; also, published in Physics Letters 23, 317 (1966). | Oct. 1966 |
| 35 | Pulse-Stimulated Radiation from a Plasma Due to an Energy-Dependent Gyrofrequency, by W. H. Kegel; also, published in Plasma Physics 9, Pergamon Press 1967, p. 23. | March 1967 |
| 36 | Echoes in Collision-Free Plasmas, by R. W. Gould | July 1967 |
| 37 | Plasma Echoes at Upper Hybrid Resonance, by L. O. Bauer, F. A. Blum and R. W. Gould | Dec. 1967 |
| 38 | Temporal and Spatial Plasma Wave Echoes, by T. M. O'Neil and R. W. Gould, July 1967; also published in The Physics of Fluids 11, 134 (1968). | July 1967 |

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|---|---|---|
| 39 | Echoes and Scattering from Plasma in a Magnetic Field by F. A. Blum | May 1968 |
| 40 | Experimental Study of the Upper Hybrid Echo in Plasmas by L. O. Bauer | May 1968 |
| 41 | Investigation of the Conductance Peaks at the Cyclotron Harmonics, by J. G. Downward and R. S. Harp | Nov. 1969 |
| | Resonance Cones in the Field Pattern of a Short Radio Frequency Probe in a Warm Anisotropic Plasma, by R. K. Fisher | April 1970 |

| | | |
|---|---|---|
| 2 | Parametric Amplification and Frequency Conversion in Magneto-Plasmas, by A. Yariv | August 1965 |
| 6 | Spontaneous and Stimulated Light Emission Due to Radiative Recombination in Forward Biased Lead Telluride p-n Junctions, P. J. A. Zoutendyk | May 1968 |

# V

# ABSTRACTS

# OF TECHNICAL REPORTS ISSUED

# UNDER CONTRACT Nonr 220(50)

# EXPERIMENTAL STUDY OF PLASMA WAVE RESONANCES IN A HOT NONUNIFORM PLASMA COLUMN

John C. Nickel

May 1964

## Abstract

The relative frequency spectrum $\omega^2/\overline{\omega_p^2}$ of plasma wave resonances in the positive column of a low pressure mercury discharge tube has been shown to depend upon the parameter $r_w^2/\overline{\lambda_D^2}$ where $r_w$ is the radius of the column, $\overline{\lambda_D^2}$ is the Debye length defined in terms of the average electron density, and $\overline{\omega_p^2}$ is the square of the average plasma frequency. This paper presents observations of both dipole and quadrupole resonance spectra made on several discharge tubes with $r_w$ ranging from 0.30 to 0.87 cm. For these measurements $r_w^2/\overline{\lambda_D^2}$ varies from about $10^2$ to $10^5$, and the best fit electron temperatures are found to be of the order of 3 ev. The average electron densities are directly measured using a cavity perturbation technique. The results of these observations are found to be in good agreement with the theory (1,2) based upon the first two moments of the correlationless Boltzmann equation in conjunction with Parker's electron density profile (3) for a low density positive column.

The results of a preliminary investigation of the effects of an axial, static magnetic field on the dipole resonance spectrum are also presented. These results indicate that in the presence of an axial magnetic field not only does the lowest resonance (approximately predicted by the cold plasma theory) split, but the next higher order resonance also splits. For the

lowest resonance, it is found that $\Delta\omega/\omega_g \approx .8 \pm .1$ , while for the next higher order resonance $\Delta\omega/\omega_g \approx .5 \pm .2$ , where $\omega_g$ is the cyclotron frequency. These preliminary results are in good accord with calculations made by Parker (1), again using the moment equation approach.

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(1) J. V. Parker, PhD Thesis, California Institute of Technology, June 1964.

(2) J. C. Nickel, J. V. Parker, R. W. Gould, Phys. Rev. Letters 11, 183 (1963).

(3) J. V. Parker, Phys. Fluids 6, 1657 (1963).

# THEORY OF PLASMA WAVE RESONANCES IN A HOT NONUNIFORM PLASMA

Jerald V. Parker

## ABSTRACT

This work is concerned with the resonant motion exhibited by a plasma column which is excited by an oscillating electric field transverse to the column. A theory is considered which includes the effects of electron temperature and of nonuniformities in the plasma electron density. In order to have a quantitative theory, the non-uniform electron densities used are calculated numerically using a theory due to Tonks and Langmuir.

The theory yields a fourth order differential equation which is integrated numerically to find the predicted resonant frequencies. The predictions are compared with experiment and show excellent agreement. It is concluded that the nonuniform electron density plays a crucial role in determining the resonant frequencies.

The effect of an axial magnetic field upon the resonances has been investigated. It is shown that the field causes each resonance to split into a right and left circularly polarized resonance whose frequencies depend on the field strength. These preliminary calculations have been checked with experiment and they give good qualitative agreement.

Possible diagnostic uses of these results are considered.

June 1964

June 1965

# DIRECTED ELECTRON VELOCITY DISTRIBUTIONS IN RARE GAS DISCHARGES USING GUARD RING PROBES

Robert H. Bond

## Abstract

An experimental technique for determining detailed properties of anisotropic electron velocity distributions is described. For a planar Langmuir probe it is shown that $g(v_z) = -\frac{m}{e^2}\frac{\partial J_p}{\partial V_p}$ where $v_z = \sqrt{2\frac{e}{m}V_p}$ and $g(v_z)$ gives the density of electrons with velocities normal to the probe in the range $v_z$ to $v_z + dv_z$. This expression is valid for any distribution function making it possible to study anisotropies merely by changing the orientation of the probe. If the distribution function is isotropic the above expression is valid for cylindrical and small spherical probes as well.

This technique is applied to the measurement of the directional properties of electron velocity distributions in the positive column of neon and helium hot cathode discharges. The necessary planar probe consists of a 0.01 inch diameter circular probe surrounded by a 0.090 inch square guard-ring. The measured distributions were Druyvesteyn in form except that all electrons were shifted in energy (in the direction of the external field) by an amount proportional to $E\lambda(v_z)$. Here $E$ is the magnitude of the external electric field and $\lambda(v_z)$ the electron mean free path as a function of $v_z$. The experimental conditions are shown to be identical with those necessary in the derivation of the Druyvesteyn distribution.

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KEGEL, Wilhelm H

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13. ABSTRACT

A plasma in a homogeneous magnetic field, excited by two short pulses at the gyrofrequency is considered. It is shown that the relativistic mass effect leads to radiation maxima after the second pulse at times that are multiples of $\tau/1 \pm D$, where $\tau$ is the time separation of the exciting pulses and $D$ is their relative strength.

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Nov. 1965

ON THE THEORY OF PULSE STIMULATED RADIATION

FROM A PLASMA

Wilhelm H. Kegel and Roy W. Gould
California Institute of Technology

ABSTRACT

By including the relativistic mass change in the motion of electrons gyrating in a slightly inhomogeneous magnetic field, it is possible to account for the cyclotron echoes observed by Hill and Kaplan.

# THEORY OF PULSE STIMULATED RADIATION FROM A PLASMA CAUSED BY THE RELATIVISTIC MASS EFFECT*

Wilhelm H. Kegel**
California Institute of Technology, Pasadena, California

December 1965

## ABSTRACT

A plasma excited by two short pulses at the electron gyrofrequency which have a time separation $\tau$ , is considered in the single particle approach. It is shown that the relativistic mass effect can lead to a series of radiation maxima after the second pulse. In the case of a cold plasma in an inhomogeneous magnetic field these maxima arise at multiples of the time $\tau$ ; in the case of a hot plasma in a homogeneous magnetic field at multiples of $\tau/|1 \pm D|$, where $D$ is the strength of the second pulse relative to the first one. The shape of the radiation maxima is given by the square of the Fourier transform of the distribution of the inhomogeneities or the initial energies, respectively. The two effects have the tendency to cancel each other. If the plasma is excited by three pulses, the time separation of the second and third pulse being $T$ , radiation maxima occur at times $t = K\tau + LT$ , ($\pm K, L = 0, 1, 2 \cdots$ but $t > 0$) after the third pulse in the case of a cold plasma with field inhomogeneities and at $t = (K\tau + LT)/|1 \pm D \pm D_2|$ in the case of a hot plasma. If collisions are taken into account the dependence on $T$ of the radiation maxima with $L = 0$ is determined by inelastic collisions only, while the other decay times are determined by all kinds of collisions.

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**On leave from the Institut für Plasmaphysik, Garching bei München, Germany.

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GOULD, Roy W.

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**13. ABSTRACT**


Reviews experimental observations and theories of pulse stimulated radiation phenomena in plasmas. The motions of an ensemble of non-interacting electrons in a magnetic field is considered and it is shown that cyclotron echoes in plasmas can arise out of various types of nonlinearities:

a) energy dependent electron cyclotron frequency,
b) energy dependent electron collision frequency,
c) energy dependent driving force.

The similarities and differences with spin and photon echoes is discussed, and several new related phenomena are also described.


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Security Classification

May 1966

# ON THE THEORY OF PULSE STIMULATED RADIATION FROM A PLASMA

Wilhelm H. Kegel and Roy W. Gould
California Institute of Technology

## ABSTRACT

By including the relativistic mass change in the motion of electrons gyrating in a slightly inhomogeneous magnetic field, it is possible to account for the cyclotron echoes observed by Hill and Kaplan.

June 1966

# Pulse Stimulated Radiation from a Plasma at Harmonics of the Gyrofrequency

Wilhelm H. Kegel*

## ABSTRACT

A magneto-plasma excited by two short pulses at the gyrofrequency or a multiple thereof, is considered in the single particle approach. After the second pulse radiation maxima arise at the gyrofrequency and its harmonics. In a situation where the time separation of these maxima is $\tau^*$ (in the simplest case $\tau^* = \tau$) at the fundamental, it is $\tau^*/n$ at the n-th harmonic.

As the resonances at the harmonics are a finite Larmor radius effect, excitation at these frequencies requires an initial energy. As an example, the case is studied where the first pulse has the gyrofrequency while the second has the frequency $2\omega_c$. In this case radiation maxima arise with $2\omega_c$ at times $t_\ell = \ell\tau$ ($\ell = 1,2,3\cdots$) after the second pulse. At the fundamental the maxima arise at times $t_\ell = (2\ell - 1)\tau$, where the maximum at the time $\tau$ is initially due to the nonlinearity during the second pulse.

*On leave from the Institut für Plasmaphysik, Garching bei München, Germany.

Sept. 1966

A NONLINEAR STUDY OF BEAM PLASMA AMPLIFICATION

Robert L. Poeschel

ABSTRACT

The interaction between an electron beam and the plasma oscillations it excites in traversing a plasma region effectively changes the magnitude and direction of the force between beam electrons. This effect has been studied theoretically and experimentally by computing and observing beam electron velocities and phases for a beam which is initially velocity modulated at frequency $\omega$ and allowed to drift through a plasma filled region of plasma frequency $\omega_p$. When $\omega > \omega_p$ the force between electrons is repulsive and effectively increases in magnitude as $\omega$ approaches $\omega_p$. When $\omega < \omega_p$, the force between electrons becomes a force of attraction, to within a given inter-electron spacing, and the maximum effect is also at the resonance condition $\omega \sim \omega_p$. This property could be used to improve the efficiency of electron bunching in a klystron type amplifier by filling the drift space with a plasma of appropriate density.

The beam behavior is studied theoretically by computing in an exact, nonlinear manner, the trajectories of a disc model electron beam which traverses a linear, dielectric model plasma. The parameters varied are the beam space charge conditions (beam current), the degree of initial velocity modulation, and the ratio of modulation frequency to plasma frequency $(\omega/\omega_p)$. Computations show that it is possible to bunch the beam electrons to within 85% of delta function bunching under some beam and plasma conditions. The electron beam behavior is studied experimentally by observing the beam electron velocity phase distribution with a crossed-field velocity analyzer, and observing the beam current waveform (density-phase distribution) using a wide-band

sampling oscilloscope. Experimental results show essentially the same beam behavior as predicted by the computations with some differences which are attributed to variation in the plasma density along the beam path.

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PULSE STIMULATED RADIATION FROM A PLASMA INVOLVING THE SECOND HARMONIC OF THE GYROFREQUENCY.

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Wilhelm H. KEGEL

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13. ABSTRACT

If a plasma is excited by two short pulses at the gyrofrequency and its second harmonic, respectively, with a time separation $\tau$ , a radiation maximum is predicted to occur at the gyrofrequency at a time $\tau$ after the second pulse.

# ECHOES IN COLLISION-FREE PLASMAS

R. W. Gould
California Institute of Technology, Pasadena, California

## ABSTRACT

It is shown that temporal echoes can occur in collision-free plasmas at various times for different wave number combinations and that spatial echoes can occur at various positions for different frequency combinations.

July 1967

Report No. 2

# PARAMETRIC AMPLIFICATION AND FREQUENCY CONVERSION IN MAGNETO-PLASMAS

Amnon Yariv

August 1965

## ABSTRACT

The problem of parametric amplification, oscillation, and frequency conversion in magnetoplasmas is considered. Two schemes are investigated

(a) The parametric modulation of the dielectric constant through charge modulation and

(b) Energy exchange via electrons undergoing cyclotron resonance between a quadrupolar rf field and a uniform frequency field.

May 1968

Report No. 6

# SPONTANEOUS AND STIMULATED LIGHT EMISSION DUE TO RADIATIVE RECOMBINATION IN FORWARD BIASED LEAD TELLURIDE p-n JUNCTIONS

P. J. A. Zoutendyk

## ABSTRACT

Since the discovery in 1962 of laser action in semiconductor diodes made from GaAs, the study of spontaneous and stimulated light emission from semiconductors has become an exciting new field of semiconductor physics and quantum electronics combined. Included in the limited number of direct-gap semiconductor materials suitable for laser action are the members of the lead salt family, i.e. PbS, PbSe and PbTe. The material used for the experiments described herein is PbTe. The semiconductor PbTe is a narrow band-gap material ($E_g$ = 0.19 electron volt at a temperature of $4.2^{\circ}$K). Therefore, the radiative recombination of electron-hole pairs between the conduction and valence bands produces photons whose wavelength is in the infrared ($\lambda \approx 6.5$ microns in air).

The p-n junction diode is a convenient device in which the spontaneous and stimulated emission of light can be achieved via current flow in the forward-bias direction. Consequently, the experimental devices consist of a group of PbTe p-n junction diodes made from p-type single crystal bulk material. The p-n junctions were formed by an n-type vapor-phase diffusion perpendicular to the (100) plane, with a junction depth of approximately 75 microns. Opposite ends of the diode structure were cleaved to give parallel reflectors, thereby forming the Fabry-Perot cavity needed for a laser oscillator. Since the emission of light originates from the recombination of injected current carriers, the nature of the radiation depends on the injection mechanism.

The total intensity of the light emitted from the PbTe diodes was observed over a current range of three to four orders of magnitude. At the low current levels, the light intensity data were correlated with data obtained on the electrical characteristics of the diodes. In the low current region (region A), the light intensity, current-voltage and capacitance-voltage data are consistent with the model for photon-assisted tunneling. As the current is increased, the light intensity data indicate the occurrence of a change in the current injection mechanism from photon-assisted tunneling (region A) to thermionic emission (region B). With the further increase of the injection level, the photon-field due to light emission in the diode builds up to the point where stimulated emission (oscillation) occurs. The threshold current at which oscillation begins marks the beginning of a region (region C) where the total light intensity increases very rapidly with the increase in current. This rapid increase in intensity is accompanied by an increase in the number of narrow-band oscillating modes. As the photon density in the cavity continues to increase with the injection level, the intensity gradually enters a region of linear dependence on current (region D), i.e. a region of constant (differential) quantum efficiency.

Data obtained from measurements of the stimulated-mode light-intensity profile and the far-field diffraction pattern (both in the direction perpendicular to the junction-plane) indicate that the active region of high gain (i.e. the region where a population inversion exists) extends to approximately a diffusion length on both sides of the junction. The data also indicate that the confinement of the oscillating modes within the diode cavity is due to a variation in the real part of the dielectric constant, caused by the gain in the medium. A value of $\tau \approx 10^{-9}$ second for the minority-carrier recombination lifetime (at a diode temperature of $20.4^{\circ}K$) is obtained from the above measurements. This value for $\tau$ is consistent with other data obtained independently for PbTe crystals.

Data on the threshold current for stimulated emission (for a diode temperature of $20.4^{\circ}K$) as a function of the reciprocal cavity length were obtained. These data yield a value of $J'_{th} = (400 \pm 80)$ amp/cm$^2$ for the threshold current in the limit of an infinitely long diode-cavity. A value of $\alpha = (30 \pm 15)$ cm$^{-1}$ is obtained for the total (bulk) cavity loss constant, in general agreement with independent measurements of free-carrier absorption in PbTe. In addition, the data provide a value of $\eta_s \approx 10\%$ for the internal spontaneous quantum efficiency. The above value for $\eta_s$ yields values of $t_b \approx \tau \approx 10^{-9}$ second and $t_s \approx 10^{-8}$ second for the nonradiative and the spontaneous (radiative) lifetimes, respectively.

The external quantum efficiency ($\eta_d$) for stimulated emission from diode J-2 (at $20.4^{\circ}K$) was calculated by using the total light intensity vs. diode current data, plus accepted values for the material parameters of the mercury-doped germanium detector used for the measurements. The resulting value is $\eta_d \approx 10\%$-$20\%$ for emission from both ends of the cavity. The corresponding radiative power output (at $\lambda \approx 6.5$ micron) is 120-240 milliwatts for a diode current of 6 amps.

May 1968

EXPERIMENTAL STUDY OF THE UPPER
HYBRID ECHO IN PLASMAS, by
Luc O. Bauer

The two-pulse stimulated radiation of dense ($10^9/cm^3 < ne \leq 10^{11}/cm^3$) nonuniform neon and argon afterglow plasma columns longitudinally immersed in a magnetic field is studied. The magnetic field is very homogeneous over the plasma volume ($\Delta B/B \sim .01\%$). If the S-band microwave pulses' center frequency is such that they resonantly excite a narrow band of plasma upper hybrid oscillations close to the maximum upper hybrid frequency of the column, strong two-pulse echoes are observed. This new echo process is called the upper hybrid echo. The echo spectrum, echo power and echo width were studied as a function of the pulse peak power P, pulse separation $\tau$, relative density $(\omega_{po}/\omega)^2$, and relative cyclotron frequency $(\omega_c/\omega)$. The complex but systematic variations of the echo properties as a function of the above-mentioned parameters are found to be in qualitative agreement with those predicted by a theory of Gould and Blum based upon a simple nonuniform unidimensional cold plasma slab model. The possible effects of electron neutral and electron ion collisions not retained in the theoretical model are discussed.

The existence of a new type of cyclotron echo, different from that of Hill and Kaplan and not predicted by the Blum and Gould model is documented. It is believed to be also of a collective effect nature and can probably be described in terms of a theory retaining some hot plasma effects.

May 1968

# ECHOES AND SCATTERING FROM PLASMA IN A MAGNETIC FIELD

Fred A. Blum

A study of the high frequency properties of a low temperature plasma column in a longitudinal magnetic field is described. The experimental observations give a relatively complete picture of the microwave (extraordinary mode) properties of the plasmas studied, encompassing continuous wave scattering and noise emission measurements, as well as the demonstration of the occurrence of related echo processes. Theoretical developments deal largely with a physical model consisting of a one-dimensional slab of cold (zero temperature) plasma which is nonuniform in the steady state and immersed in a uniform magnetic field. Data on the continuous wave reflection and noise emission from some afterglow rare gas discharges are given. The electron temperature in these plasmas is low, approaching room temperature. The reflection and emission are measured as a function of magnetic field in the vicinity of electron cyclotron resonance with electron density as a parameter. The electron densities are such that $(\omega_p/\omega) \leq 1$ , where $\omega_p$ is the electron plasma frequency and $\omega$ is the signal frequency. Both types of experiment show the presence of collective effects which yield a normal mode spectrum strongly dependent on the electron density. A broad peak is observed in the region $(\omega_c/\omega) \leq 1$ where $\omega_c$ is the electron cyclotron frequency. This peak shifts to lower values of $(\omega_c/\omega)$ and broadens as the electron density increases. For all values of electron density, a sharp peak is found very close to $(\omega_c/\omega) = 1$ , the cyclotron resonance condition. The experimental and theoretical results suggest that the phenomena observed involve resonance effects

at the upper hybrid frequencies ($\omega_h^2 = \omega_c^2 + \omega_p^2$) of the plasma. Data are also given on a new two-pulse echo process which occurs in these afterglow plasmas. The results establish the intimate relation between the echoes and the upper hybrid normal modes studied in the CW experiments, demonstrating the dominant role played by collective effects in the formation of this echo. A weakly nonlinear cold plasma theory yields upper hybrid echoes which are strongest in a narrow band of frequencies near the maximum upper hybrid frequency of the nonuniform plasma, in agreement with experiment. Furthermore, large signal computations of the dependence of the echo amplitude on excitation pulse separation and amplitude show a complex behavior in qualitative agreement with experiment. As a supplementary topic, the properties of echoes from a general collection of anharmonic oscillators are discussed. The oscillators in this discussion are a general mathematical analog of the upper hybrid normal modes of a cold nonuniform plasma. Through emphasis of effects due to the finite width of the excitation pulses, the calculations show explicitly the role of the various characteristics of the oscillators in echo processes, further delineating the general features thought requisite of classical multiple-pulse echo systems.

Nov. 1969

INVESTIGATION OF THE CONDUCTANCE PEAKS AT THE CYCLOTRON HARMONICS*

J. G. Downward and R. S. Harp

We wish to report on a theoretical and experimental study of conductance peaks at the cyclotron harmonics in a cylindrical plasma capacitor. Possible applications of this work to plasma diagnostics will be mentioned briefly.

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*Talk given at the November 12 APS Plasma Physics Meeting in Los Angeles, California. Research sponsored by U.S.Office of Naval Research.

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April 1970

RESONANCE CONES IN THE FIELD PATTERN OF A SHORT RADIO FREQUENCY PROBE IN A WARM ANISOTROPIC MEDIA

R. K. Fisher

An experimental investigation of the angular field pattern of a small radio frequency probe in a plasma in a magnetic field is described. The field is observed to become very large along a resonance cone whose axis is parallel to the static magnetic field and whose opening angle is observed to vary with incident probe frequency, electron cyclotron frequency, and electron plasma frequency in agreement with simple cold plasma dielectric theory. The use of the resonance cone angle as a diagnostic tool to measure the plasma density in a plasma in a magnetic field is discussed. It is noted that similar cones might be expected near the ion cyclotron frequency.

The relationship of these cones to the limiting phase- and group-velocity cones which appear in the theory of plane wave propagation is discussed. The necessity for examining the allowed directions of the group velocity rather than the allowed directions of the phase velocity and customary phase velocity plots when determining whether propagation between two remote points in a plasma is possible, is emphasized.

The addition of electron thermal velocities to the theory is examined in the limit of a large static magnetic field. The resonance cone angle is shifted to a slightly smaller angle than that predicted by cold plasma theory, and a fine structure appears inside the cones and is shown to result from an interference between a fast electromagnetic wave and a slow plasma wave. The interference structure is observed experimentally, and measurements of the angular intereference spacing are shown to agree with the warm plasma theory.

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13. ABSTRACT


This report covers briefly the research performed under Contract Nonr 220(50) between Sept. 1, 1963 and Sept. 1, 1969. Research generally covered the following areas:

Plasma wave resonances in spatially non-uniform plasmas
Cyclotron and upper hybrid echo phenomena in plasmas
Plasma wave echoes
Cyclotron harmonic waves in plasmas
Resonance cones in anisotropic plasmas
Recombination radiation from forward biased p-n junctions
Electro-optic effect
Infrared absorption in gallium arsenide
Modes in optical resonators with gain

The report is merely a summary of research. Details of this work may be found in referenced reports and articles.

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